

Pulsars revived by gravitational waves

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Abstract. Binary neutron stars mergers that are expected to be the most powerful source of energy in the Universe definitely exist in nature, as is proven by the observed behavior of the Hulse-Taylor binary radio pulsar (Hulse, Taylor, 1975). Though most of energy in such events is radiated in gravitational waves, there probably exist several mechanisms giving also electromagnetic radiation. We propose a new one, involving a revival of the radio pulsar several orbital cycles before the merger.

Key words: pulsars: general — pulsars: binary — stars: neutron — gravitational waves — binaries: mergers

1. Introduction

Observations of binary radio pulsars (fast rotating neutron stars) made it possible to determine that the orbits of binaries contract in exact correspondence with the Einstein's formula for emission of gravitational waves

$$L_{gw} = \frac{4}{5} \frac{G^4}{c^5} \frac{M^5}{a^5}$$

where M is the mass of the components, a is the semi-major axis of the binary, G and c are the gravitational constant and velocity of light, respectively. Moreover, in many cases the characteristic time for this orbit contraction is less than the age of Galaxy, which implies that the neutron star mergers in the Universe should necessarily occur (Hulse, Taylor, 1975).

The merger, if the stars are compact, is inevitably accompanied by energy output of the order of Mc^2 in a very small time of the order of R_g/c , so the power of this process is close to the maximal possible value $L_{GR} = E_{Plank}/t_{Plank} = c^5/G \sim 10^{59}$ erg/s (Lipunov, 1993). Of course, much of this energy is carried away by gravitational waves that may be soon detected by the new laser interferometers (Thorne, 1994) that are now under construction or under consideration (Danzmann et al., 1993), but probably some part will be radiated as electromagnetic waves.

The analysis of the modern scenario of evolution of binaries provides the rate of the neutron star merger events in the Galaxy of once per $10^4 - 10^6$ years (Lipunov et al., 1987, Tutukov, Yungelson, 1992, van den Heuvel, 1994, Lipunov et al., 1995, Portegies Zwart, Spreeuw, 1995) for various distributions of initial parameters. The least estimate (1 per 10^6 years) of this rate is given by Phinney (1991) on the basis of the observed population of binary pulsars.

Though the value of the merger rate is not significant for existence of the proposed mechanism of radio revival, we will make the estimations of its observational properties on the basis of the most optimistic estimate of the rate: 10^{-4} yr⁻¹.

As the total mass of all galaxies in the Universe is approximately 10^9 times greater than the mass of our Galaxy, such event happens approximately once per minute. The enormous energy released in this process makes it attractive for explanation of gamma-ray bursts (Blinnikov et al., 1991, Paczyński, 1991, Paczyński, 1991), but though it is still not clear what part of energy is transformed into electromagnetic radiation and what is the mechanism of such transformation.

In this paper we show that during the inspiral of two neutron stars that precedes their coalescence if at least one of them has a strong magnetic field, the conditions for revival of the classical pulsar mechanism (Gold, 1969, Goldreich, Julian, 1969) would necessarily arise due to fast orbital motion.

2. The Mechanism for the Pulsar Revival

Let us remind that the energy output of the pulsars is caused by the spinning of a dipole magnetic field and is well described by the classical formula for the magnetic dipole emission (Landau, Lifshitz, 1986):

$$L_m = \frac{2}{3c^3} \mu^2 \omega^4$$

where μ is the magnetic dipole momentum and ω is the spin angular velocity.

Now we observe about 600 radio pulsars losing their spin energy in accordance with this formula. Usually their luminosity does not exceed several units of the luminosity of the Crab pulsar (10^{38} erg s⁻¹). The reason is that pulsars are evidently born with relatively long period of the order 10^{-2} sec while the magnetic dipole momentum is $\mu \approx 10^{30}$ G cm³. So the standard pulsars have rather low luminosity and in several million years spin down and die.

The fate of a neutron star in a close binary system is quite different. During the accretion phase the neutron star is spun up to periods close to the critical ($T_{cr} = 2\pi/\omega_{cr} \sim 1$ ms), what leads to the revival of the pulsar mechanism after the accretion stops even if the magnetic field would be reduced by that time.

During the inspiral the orbital period of the binary decreases reaching the minimum value of 1 ms when the components come into mechanical contact.

In all further calculations we assume the masses of both neutron stars to be equal to $M = 1.4M_{\odot}$; the orbit to be circular with a separation between the components a . The neutron star radius R is taken 10 km.

2.1. The Synchronized Dipole

Only for the purpose of comparison, assume the really impossible case if the neutron star spin is synchronized with the orbital motion. Then $\omega_{spin} = \omega_{orb}$ – so the neutron star will behave like a classical pulsar with a very high frequency, emitting energy according to the magnetic dipole formula. In practice, due to enormous increase of ω_{orb} it will essentially exceed the spin angular velocity $\omega_{spin} \sim 0.1 \dots 10$ s⁻¹ after some moment of time, and the tidal forces will not be strong enough to spin the neutron star up to ω_{orb} , so synchronization will be impossible.

It is so because the tidal relaxation time that can be derived from observations of pulsar glitches is of the order of several days which is much greater than the lifetime of the binary system with such orbital period.

Thus, below we can assume $\omega_{spin} \ll \omega_{orb}$, or for crude estimate, $\omega_{spin} = 0$.

2.2. The Orbital Quadrupole

If a magnetic dipole μ performs orbital motion say, on a circular orbit of a radius a , the total quadrupole moment \mathbf{D} in the inertial frame corresponding to the center of the orbit will change as

$$D^2(t) = 18\mu^2 a^2 \left(1 + \frac{\cos^2 \theta(t)}{3} \right)$$

where θ is the angle between the orbital radius and the magnetic dipole axis, $\cos \theta(t) = \cos i \cos \alpha(t)$, where i is the dipole inclination to the orbit plane and α is the phase of orbital motion.

It should cause magnetic quadrupole energy losses with rate

$$L = \frac{\ddot{D}^2}{180c^5},$$

where

$$\ddot{D} = \omega_{orb}^3 a \mu$$

2.3. The Induced dipole

Consider the binary system containing two neutron stars with low spin frequencies $\omega \sim 0$, one of them having significant magnetic field. Because of this enormous increase of ω_{orb} it will essentially exceed the spin angular velocity $\omega_{spin} \sim 0.1 \dots 10$ s⁻¹ after some moment of time, so we can assume $\omega_{spin} \ll \omega_{orb}$, or for crude estimate, $\omega_{spin} = 0$. The ω_{spin} does not significantly change during the inspiral because the tidal forces that tend to synchronize the spin and orbital motion are negligibly small in this case.

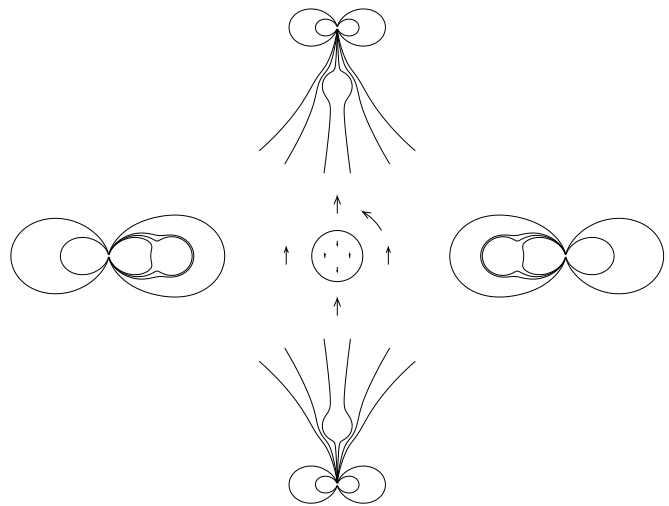


Fig. 1. The field configurations in 4 positions of a magnetic dipole (the big arrows) near a superconducting sphere. The small arrows represent the induced dipole positions.

In order to find the field configuration, let us replace the magnetized star by a dipole μ_0 tilted to the angle α to the orbital axis and solve the magnetostatic problem of a dipole in the vicinity of a superconducting sphere. The result is (see fig.1) that the induced magnetic field of the sphere will be equal to the magnetic field of the dipole $\mu_1 = \mu_0 \left(\frac{R}{a}\right)^3$ tilted oppositely to the tilt of the outer dipole and shifted from the center of the sphere to the distance R^2/a . If we rotate the dipole μ_0 around the sphere, the induced dipole μ_1 will rotate twice. This means that if the dipole is orbiting around the sphere, the total dipole momentum $\mu = \mu_0 + \mu_1$ would consist of a constant part and a part oscillating with a double orbital frequency, which implies the existing of magnetic dipole energy loss

$$L(t) = \frac{8\mu^2 \sin^2 \alpha \omega_{orb}^8}{3c^3 \omega_{cr}^4} \sim 5 \cdot 10^{32} \sin^2 \alpha \mu_{30}^2 t^{-3} \text{ erg s}^{-1}$$

that should be carried away from the system by electromagnetic radiation or accelerated charged particles.

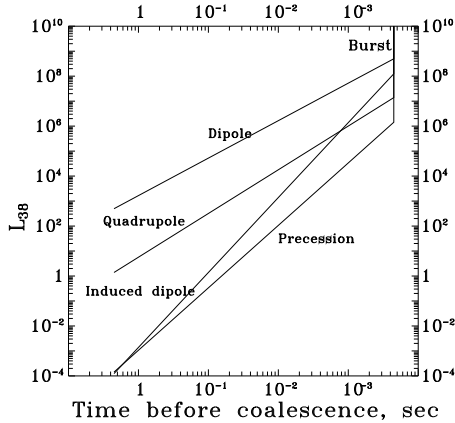


Fig. 2. The light curve of the revived pulsar with $\mu = 10^{30} \text{ G cm}^3$. $L_{38} = L/10^{38} \text{ erg/s}$.

The infinite growth of luminosity (fig 2.) is in fact terminated by the finite size of the stars. We can apply the above formula only when the stars can be considered as two separate bodies, i.e. the distance between them is greater than $2R$. So the maximum luminosity reached when the stars come into surface contact will be

$$L_{max} \sim 8 \cdot 10^{41} \sin^2 \alpha \mu_{30}^2 \text{ erg s}^{-1}$$

Of course, in the case of the induced dipole the configuration of the magnetosphere is quite different from that in the case of a solitary pulsar. The most important condition for particle acceleration is the existence of a vacuum region (at least the density of the charges should be less than in Goldreich – Julian case) where the electric field would be not orthogonal to the magnetic field. We point out that in our case at least near the neutral points where the magnetic field is equal to zero we have a nonzero electric field of both relativistic ($\frac{v}{c}B$) and inductive ($\partial B/\partial t$) origin.

We emphasize that this mechanism is a modification of classical unipolar inductor mechanism of particle acceleration. It is essentially different from that proposed by Nulsen and Fabian (Nulsen, Fabian, 1984) for Geminga.

2.4. The Lense-Thirring Precession

In strong gravitational field of an orbiting binary star the Lense-Thirring precession of the stars should occur. Its

frequency is (Barker, O’Connell, 1978)

$$\Omega_g \approx \frac{7}{8} \frac{(GM)^{2/3} \omega_{orb}^{5/3}}{2^{1/3} c^5}$$

It leads to rotation of the magnetic dipole moment at the same frequency and thus, magnetic dipole energy losses.

2.5. Summary

Thus the pre-merger, inspiral of the neutron stars should be accompanied by all types of pulsar activity which should be displayed, according to the observed properties of Crab-like pulsars, in a wide range of electromagnetic spectrum from radio to gamma rays. The characteristic feature of this pulsar activity is that the frequency of its pulsations ($\omega = 2\omega_{orb}$ for induced dipole and $\omega = \omega_{orb}$ for other cases) should increase with time according to the gravitational radiation orbit contraction law.

As the effect might be observed both as electromagnetic radiation and as gravitational radiation waveform, we present a summary of both electromagnetic luminosity L and its ratio to gravitational wave luminosity L/L_{gw} in the table 2.5. In this table we took $x = R/R_g = 3$, $\omega_{cr} = \sqrt{GM/R^3}$, $R_g = \sqrt{2GM/c^2}$, $L_{em} = \frac{3}{2} \frac{\mu^2 c}{R_g^4}$ - the “maximal” electromagnetic luminosity. v/c is the ratio of the characteristic orbital velocity to the velocity of light.

3. Discussion

As the classical pulsars were first discovered in the radio wave band, we can suppose that the most prospective for the observations of the inspiralling neutron stars could be also radio emission.

Suppose that one of the stars has the characteristics of the Crab pulsar. Then at the spin frequency close to the orbital one of the inspiralling binaries ($\sim 1 \text{ ms}$) its luminosity should be 10^6 times higher. This means that this coalescing binary will display a radio burst with a flux equal to the flux from the Crab from distances of 2 Mpc, and if we take into account that the sensitivity of modern radio telescopes allows to see pulsars 1000 times less luminous than the Crab we can see this bursts from the distances of 60 Mpc. The rate of these events in this part of the Universe is optimistically estimated as several events per year and even with accounting for the beam of the telescopes we can expect their observation to be possible.

In the optical band, the revived pulsar should have the maximum absolute magnitude $M = -9$. We can see that the problem of its detection is rather difficult in comparison with the detection of distant supernovae.

Of course, it would be attractive to connect the proposed mechanism with the gamma-ray bursts themselves. In fact, it is possible to suppose following Usov (Usov, 1992) that some fraction $\sim 1\%$ of the pulsars have enormously strong magnetic fields ($10^{15} - 10^{16} \text{ G}$), then

Table 1. The characteristics of all 4 mechanisms of pulsar revival.

Mechanism	L	$L, \text{erg/s}$	L/L_{gw}
Dipole	$L_{em} \left(\frac{1}{2x^3}\right)^2 \left(\frac{\omega}{\omega_{cr}}\right)^4$	$\sim 5.0 \cdot 10^{46} \left(\frac{\omega}{\omega_{cr}}\right)^4$	$\frac{1}{2^{11}} \left(\frac{L_{em}}{L_{GR}}\right) \left(\frac{v}{c}\right)^2 \sim 4.8 \cdot 10^{-13} \left(\frac{v}{c}\right)^2$
Quadrupole	$L_{em} \frac{2^{1/3}}{60x^7} \left(\frac{\omega}{\omega_{cr}}\right)^{14/3}$	$\sim 1.4 \cdot 10^{45} \left(\frac{\omega}{\omega_{cr}}\right)^{14/3}$	$\left(\frac{L_{em}}{L_{GR}}\right) \frac{1}{2^{11 \frac{1}{3} \cdot 15}} \left(\frac{v}{c}\right)^4 \sim 2.6 \cdot 10^{-14} \left(\frac{v}{c}\right)^4$
Induced dipole	$L_{em} \frac{1}{16x^6} \left(\frac{\omega}{\omega_{cr}}\right)^8$	$\sim 1.2 \cdot 10^{46} \left(\frac{\omega}{\omega_{cr}}\right)^8$	$\left(\frac{L_{em}}{L_{GR}}\right) \frac{x^6}{2^{17}} \left(\frac{v}{c}\right)^{14} \sim 5.5 \cdot 10^{-12} \left(\frac{v}{c}\right)^{14}$
Precession	$L_{em} \left(\frac{7}{8}\right)^4 \frac{1}{2^{10/3} x^{10}} \left(\frac{\omega}{\omega_{cr}}\right)^{20/3}$	$\sim 1.4 \cdot 10^{44} \left(\frac{\omega}{\omega_{cr}}\right)^{20/3}$	$2^{20} \left(\frac{L_{em}}{L_{GR}}\right) \left(\frac{7}{8}\right)^4 \left(\frac{v}{c}\right)^{20} \sim 2.6 \cdot 10^{-14} \left(\frac{v}{c}\right)^{20}$

the pulsar mechanism can provide the luminosity required for the cosmological gamma-ray bursts. This seems reasonable, as the total rate of the neutron star mergers is 100–1000 times higher than the rate of gamma-ray bursts in the cosmological model. However, one should also take into account the anisotropy of the radiation necessarily arising in the pulsar mechanism, that is used to balance the rates of the gamma-ray bursts and neutron star mergers (Lipunov et al., 1995). We however note that irrespectively of the real nature of gamma-ray bursts, the gravitational wave bursts that mainly originate from the coalescence of the neutron stars should have the pulsar-like precursors.

Obviously, on the last phase of the inspiral when the neutron star crust is strongly deformed and the neutron stars themselves are destroyed – the pulsar mechanism should be damped to some degree.

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